UNITED STATES PATENT APPLICATION

METHOD AND APPARATUS FOR TREATING IRREGULAR VENTRICULAR CONTRACTIONS SUCH AS DURING ATRIAL ARRHYTHMIA

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Method and Apparatus for Treating Irregular Ventricular Contractions Such As During Atrial Arrhythmia

Cross Reference To Related Applications

5   This application is related to the following co-pending, commonly assigned patent applications: "Cardiac Rhythm Management System Promoting Atrial Pacing," serial number 09/316 68 2, (Attorney Docket No. 00279.113US1); "Cardiac Rhythm Management System With Atrial Shock Timing Optimization," serial number 09/316 74 1, (Attorney Docket No. 00279.142US1); and "System

10   Providing Ventricular Pacing and Biventricular Coordination," serial number 09/316 588, (Attorney Docket No. 00279.160US1); each of which are filed on even date herewith, each of which disclosure is herein incorporated by reference in its entirety.

Technical Field

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The present system relates generally to cardiac rhythm management systems and particularly, but not by way of limitation, to a method and apparatus for treating irregular ventricular contractions, such as during an atrial arrhythmia.

Background

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When functioning properly, the human heart maintains its own intrinsic rhythm, and is capable of pumping adequate blood throughout the body's circulatory system. However, some people have irregular cardiac rhythms, referred to as cardiac arrhythmias. Such arrhythmias result in diminished blood circulation. One

25   mode of treating cardiac arrhythmias uses drug therapy. Drugs are often effective at restoring normal heart rhythms. However, drug therapy is not always effective for treating arrhythmias of certain patients. For such patients, an alternative mode of treatment is needed. One such alternative mode of treatment includes the use of a cardiac rhythm management system. Such systems are often implanted in the

30   patient and deliver therapy to the heart.

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Cardiac rhythm management systems include, among other things, pacemakers, also referred to as pacers. Pacers deliver timed sequences of low energy electrical stimuli, called pace pulses, to the heart, such as via an intravascular leadwire or catheter (referred to as a "lead") having one or more electrodes disposed in or about the heart. Heart contractions are initiated in response to such pace pulses (this is referred to as "capturing" the heart). By properly timing the delivery of pace pulses, the heart can be induced to contract in proper rhythm, greatly improving its efficiency as a pump. Pacers are often used to treat patients with bradyarrhythmias, that is, hearts that beat too slowly, or irregularly.

Cardiac rhythm management systems also include cardioverters or defibrillators that are capable of delivering higher energy electrical stimuli to the heart. Defibrillators are often used to treat patients with tachyarrhythmias, that is, hearts that beat too quickly. Such too-fast heart rhythms also cause diminished blood circulation because the heart isn't allowed sufficient time to fill with blood before contracting to expel the blood. Such pumping by the heart is inefficient. A defibrillator is capable of delivering an high energy electrical stimulus that is sometimes referred to as a defibrillation countershock. The countershock interrupts the tachyarrhythmia, allowing the heart to reestablish a normal rhythm for the efficient pumping of blood. In addition to pacers, cardiac rhythm management systems also include, among other things, pacer/defibrillators that combine the functions of pacers and defibrillators, drug delivery devices, and any other implantable or external systems or devices for diagnosing or treating cardiac arrhythmias.

One problem faced by cardiac rhythm management systems is the proper treatment of ventricular arrhythmias that are caused by atrial tachyarrhythmias such as atrial fibrillation. Atrial fibrillation is a common cardiac arrhythmia which reduces the pumping efficiency of the heart, though not to as great a degree as in ventricular fibrillation. However, this reduced pumping efficiency requires the ventricle to work harder, which is particularly undesirable in sick patients that cannot tolerate additional stresses. As a result of atrial fibrillation, patients may be

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required to limit their activity and exercise.

Although atrial fibrillation, by itself, is usually not life-threatening, prolonged atrial fibrillation may be associated with strokes, which are thought to be caused by blood clots forming in areas of stagnant blood flow. Treating such blood clots requires the use of anticoagulants. Atrial fibrillation may also cause pain, dizziness, and other irritation to the patient.

An even more serious problem, however, is that atrial fibrillation may induce irregular ventricular heart rhythms by processes that are yet to be fully understood. Such induced ventricular arrhythmias compromise pumping efficiency even more drastically than atrial arrhythmias. For these and other reasons, there is a need for a method and apparatus for treating irregular ventricular contractions during atrial arrhythmias such as atrial fibrillation.

Summary of the Invention

The present system provides a method and apparatus for treating irregular ventricular contractions, such as during atrial arrhythmias (e.g., atrial fibrillation), or otherwise. The present system provides many advantages. Among other things, it is capable of treating irregular ventricular heart contractions, such as during atrial tachyarrhythmias. It provides a first indicated pacing rate that increases for sensed ventricular beats and decreases for paced ventricular beats. The system delivers more pacing during irregular sensed beats (such as during atrial tachyarrhythmias including atrial fibrillation or the like) and less pacing when sensed beats are regular. In a stable heart, the first indicated pacing rate is typically less than the intrinsic heart rate. This avoids unnecessary pacing of the heart when heart rhythms are substantially stable, allowing the heart to beat normally and at its own intrinsic heart rate.

One aspect of the system permits it to avoid rapid changes in heart rate, and to keep heart rate within acceptable upper and lower limits. The system allows the rate to become more regular and to approach a stable rhythm. This provides improved comfort of the patient experiencing irregular ventricular contractions. In a

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further embodiment, the system includes a second indicated pacing rate, such as a sensor-indicated rate, and provides pacing therapy based on both the first and second indicated pacing rates. Other aspects of the invention will be apparent on reading the following detailed description of the invention and viewing the drawings that

5   form a part thereof.

In one embodiment, the system obtains V-V intervals between ventricular beats. A first indicated pacing interval is computed based at least partially on a most recent V-V interval duration and a previous value of the first indicated pacing interval. Pacing therapy is provided based on the first indicated pacing interval.

10   In a further embodiment, the first indicated pacing interval is adjusted by an amount based at least on the most recent V-V interval duration and the previous value of the first indicated pacing interval, if the most recent V-V interval is concluded by an intrinsic beat. If, however, the most recent V-V interval is concluded by a paced beat, then the first indicated pacing interval is increased by an

15   amount based at least on the most recent V-V interval duration and the previous value of the first indicated pacing interval.

In another embodiment, the system detects an atrial tachyarrhythmia. The system obtains V-V intervals between ventricular beats. A first indicated pacing interval is computed based at least partially on a most recent V-V interval duration

20   and a previous value of the first indicated pacing interval. Pacing therapy is provided based on the first indicated pacing interval, if the atrial tachyarrhythmia is present.

One embodiment provides a cardiac rhythm management system that includes, among other things, a ventricular sensing circuit, a controller, and a

25   ventricular therapy circuit. The controller includes a V-V interval timer, a first register, for storing information associated with a first indicated pacing interval, and a filter that updates the first indicated pacing interval based on the V-V interval timer and the information stored in the first register. Other aspects of the invention will be apparent on reading the following detailed description of the invention and

30   viewing the drawings that form a part thereof.

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Brief Description of the Drawings

In the drawings, like numerals describe substantially similar components throughout the several views. Like numerals having different letter suffixes represent different instances of substantially similar components.

Figure 1 is a schematic drawing illustrating generally one embodiment of portions of a cardiac rhythm management system and an environment in which it is used.

Figure 2 is a schematic drawing illustrating one embodiment of a cardiac rhythm management device coupled by leads to a heart.

Figure 3 is a schematic diagram illustrating generally one embodiment of portions of a cardiac rhythm management device coupled to a heart.

Figure 4 is a schematic diagram illustrating generally one embodiment of a controller.

Figure 5 is a schematic diagram illustrating generally one conceptualization of portions of a controller.

Figure 6 is a signal flow diagram illustrating generally one conceptual embodiment of operating a filter.

Figure 7 is a signal flow diagram illustrating generally another conceptualization of operating the filter.

Figure 8 is a signal flow diagram illustrating generally a further conceptualization of operating the filter.

Figure 9 is a schematic diagram illustrating generally another conceptualization of portions of a controller.

Figure 10 is a schematic diagram illustrating generally a further conceptualization of portions of a controller.

Figure 11 is a graph illustrating generally one embodiment of operating a filter to provide a first indicated pacing rate, such as a VRR indicated rate, for successive ventricular heart beats.

Figure 12 is a graph illustrating generally another embodiment of operating a filter to provide the first indicated pacing rate, such as a VRR indicated rate, and

delivering therapy based on the first indicated pacing rate and based on a second indicated pacing rate, such as a sensor indicated rate.

Figure **13** is a graph illustrating generally another illustrative example of heart rate vs. time according to a VRR algorithm spreadsheet simulation.

5   Figure **14** is a graph illustrating generally one embodiment of using at least one of coefficients *a* and *b* as a function of heart rate (or a corresponding time interval).

Detailed Description

10   In the following detailed description, reference is made to the accompanying drawings which form a part hereof, and in which is shown by way of illustration specific embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention, and it is to be understood that the embodiments may be combined, or that other embodiments may be utilized and that structural, logical and electrical changes may be made without departing from the spirit and scope of the present invention. The following detailed description is, therefore, not to be taken in a limiting sense, and the scope of the present invention is defined by the appended claims and their equivalents. In the drawings, like numerals describe substantially similar

20 components throughout the several views. Like numerals having different letter suffixes represent different instances of substantially similar components.

The present methods and apparatus will be described in applications involving implantable medical devices including, but not limited to, implantable cardiac rhythm management systems such as pacemakers, cardioverter/defibrillators,

25 and pacer/defibrillators. However, it is understood that the present methods and apparatus may be employed in unimplanted devices, including, but not limited to, external pacemakers, cardioverter/defibrillators, pacer/defibrillators, monitors, programmers and recorders.

Problems Associated With Atrial Arrhythmias

30   As stated earlier, one potential cause of irregularity of ventricular

contractions arises during atrial tachyarrhythmias, such as atrial fibrillation. During atrial fibrillation, irregular ventricular contractions may be caused by a conducted atrial tachyarrhythmia, then pacing the ventricle will regularize the ventricular heart rate by establishing retrograde conduction from the ventricle. This, in turn, is

5   believed to block forward conduction of atrial signals through the atrioventricular (A-V) node. As a result, irregular atrial signals do not trigger resulting irregular ventricular contractions.

One therapy for treating irregular ventricular contractions during atrial fibrillation is to increase the ventricular heart rate by pacing the ventricle at a higher

10   rate than the unpaced (intrinsic) ventricular heart rate. Such therapy is believed to decrease the discomfort experienced by the patient having atrial arrhythmia because it regulates the ventricular contractions to avoid short periods between contractions and/or long periods without a contraction. Such therapy is also believed to decrease the ability of the atrial fibrillation to induce irregular ventricular contractions.

15   An increase in rate of ventricular contractions, however, must be done carefully to avoid pacing the heart at an unnecessarily high rate. Furthermore, such a therapy should not impose pacing where normal or "intrinsic" heart pacing is adequate such as, for example, when atrial tachyarrhythmias no longer cause disorder of ventricular contractions. As long as the heart is actively paced, it may be

20   difficult or impossible to determine when to cease such a therapy. One advantage of the present system is that it allows intrinsic ventricular rhythms, if such rhythms are regular, but provides pacing that stabilizes ventricular rhythms if they become irregular, as discussed below.

General System Overview and Examples

25   This document describes, among other things, a cardiac rhythm management system providing a method and apparatus for treating irregular ventricular contractions during atrial arrhythmia. Figure 1 is a schematic drawing illustrating, by way of example, but not by way of limitation, one embodiment of portions of a cardiac rhythm management system 100 and an environment in which it is used. In

30   Figure 1, system 100 includes an implantable cardiac rhythm management device

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105, also referred to as an electronics unit, which is coupled by an intravascular endocardial lead 110, or other lead, to a heart 115 of patient 120. System 100 also includes an external programmer 125 providing wireless communication with device 105 using a telemetry device 130. Catheter lead 110 includes a proximal end

5   135, which is coupled to device 105, and a distal end 140, which is coupled to one or more portions of heart 115.

Figure 2 is a schematic drawing illustrating, by way of example, but not by way of limitation, one embodiment of device 105 coupled by leads 110A-B to heart 115, which includes a right atrium 200A, a left atrium 200B, a right ventricle 205A,

10   a left ventricle 205B, and a coronary sinus 220 extending from right atrium 200A. In this embodiment, atrial lead 110A includes electrodes (electrical contacts) disposed in, around, or near an atrium 200 of heart 115, such as ring electrode 225 and tip electrode 230, for sensing signals and/or delivering pacing therapy to the atrium 200. Lead 110A optionally also includes additional electrodes, such as for

15   delivering atrial and/or ventricular cardioversion/defibrillation and/or pacing therapy to heart 115.

In Figure 2, a ventricular lead 110B includes one or more electrodes, such as tip electrode 235 and ring electrode 240, for delivering sensing signals and/or delivering pacing therapy. Lead 110B optionally also includes additional electrodes,

20   such as for delivering atrial and/or ventricular cardioversion/defibrillation and/or pacing therapy to heart 115. Device 105 includes components that are enclosed in a hermetically-sealed can 250. Additional electrodes may be located on the can 250, or on an insulating header 255, or on other portions of device 105, for providing unipolar pacing and/or defibrillation energy in conjunction with the electrodes

25   disposed on or around heart 115. Other forms of electrodes include meshes and patches which may be applied to portions of heart 115 or which may be implanted in other areas of the body to help "steer" electrical currents produced by device 105. The present method and apparatus will work in a variety of configurations and with a variety of electrical contacts or "electrodes."

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Example Cardiac Rhythm Management Device

Figure **3** is a schematic diagram illustrating generally, by way of example, but not by way of limitation, one embodiment of portions of device **105**, which is coupled to heart **115**. Device **105** includes a power source **300**, an atrial sensing

5   circuit **305**, a ventricular sensing circuit **310**, a ventricular therapy circuit **320**, and a controller **325**.

Atrial sensing circuit **305** is coupled by atrial lead **110A** to heart **115** for receiving, sensing, and/or detecting electrical atrial heart signals. Such atrial heart signals include atrial activations (also referred to as atrial depolarizations or P-

10   waves), which correspond to atrial contractions. Such atrial heart signals include normal atrial rhythms, and abnormal atrial rhythms including atrial tachyarrhythmias, such as atrial fibrillation, and other atrial activity. Atrial sensing circuit **305** provides one or more signals to controller **325**, via node/bus **327**, based on the received atrial heart signals. Such signals provided to controller **325** indicate,

15   among other things, the presence of atrial fibrillation.

Ventricular sensing circuit **310** is coupled by ventricular lead **110B** to heart **115** for receiving, sensing, and/or detecting electrical ventricular heart signals, such as ventricular activations (also referred to as ventricular depolarizations or R-waves), which correspond to ventricular contractions. Such ventricular heart signals

20   include normal ventricular rhythms, and abnormal ventricular rhythms, including ventricular tachyarrhythmias, such as ventricular fibrillation, and other ventricular activity, such as irregular ventricular contractions resulting from conducted signals from atrial fibrillation. Ventricular sensing circuit **310** provides one or more signals to controller **325**, via node/bus **327**, based on the received ventricular heart signals.

25   Such signals provided to controller **325** indicate, among other things, the presence of ventricular depolarizations, whether regular or irregular in rhythm.

Ventricular therapy circuit **320** provides ventricular pacing therapy, as appropriate, to electrodes located at or near one of the ventricles **205** of heart **115** for obtaining resulting evoked ventricular depolarizations. In one embodiment,

30   ventricular therapy circuit **320** also provides cardioversion/defibrillation therapy, as

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appropriate, to electrodes located at or near one of the ventricles **205** of heart **115**, for terminating ventricular fibrillation and/or other ventricular tachyarrhythmias.

Controller **325** controls the delivery of therapy by ventricular therapy circuit **320** and/or other circuits, based on heart activity signals received from atrial sensing
5   circuit **305** and ventricular sensing circuit **310**, as discussed below. Controller **325** includes various modules, which are implemented either in hardware or as one or more sequences of steps carried out on a microprocessor or other controller. Such modules are illustrated separately for conceptual clarity; it is understood that the various modules of controller **325** need not be separately embodied, but may be
10   combined and/or otherwise implemented, such as in software/firmware.

In general terms, sensing circuits **305** and **310** sense electrical signals from heart tissue in contact with the catheter leads **110A-B** to which these sensing circuits **305** and **310** are coupled. Sensing circuits **305** and **310** and/or controller **325** process these sensed signals. Based on these sensed signals, controller **325** issues
15   control signals to therapy circuits, such as ventricular therapy circuit **320**, if necessary, for the delivery of electrical energy (e.g., pacing and/or defibrillation pulses) to the appropriate electrodes of leads **110A-B**. Controller **325** may include a microprocessor or other controller for execution of software and/or firmware instructions. The software of controller **325** may be modified (e.g., by remote
20   external programmer **105**) to provide different parameters, modes, and/or functions for the implantable device **105** or to adapt or improve performance of device **105**.

In one further embodiment, one or more sensors, such as sensor **330**, may serve as inputs to controller **325** for adjusting the rate at which pacing or other therapy is delivered to heart **115**. One such sensor **330** includes an accelerometer
25   that provides an input to controller **325** indicating increases and decreases in physical activity, for which controller **325** increases and decreases pacing rate, respectively. Another such sensor includes an impedance measurement, obtained from body electrodes, which provides an indication of increases and decreases in the patient's respiration, for example, for which controller **325** increases and decreases
30   pacing rate, respectively. Any other sensor **330** providing an indicated pacing rate

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can be used.

Figure **4** is a schematic diagram illustrating generally, by way of example, but not by way of limitation, one embodiment of controller **325** that includes several different inputs to modify the rate at which pacing or other therapy is delivered. For 5 example, Input #1 may provide information about left ventricular rate, Input #2 may provide an accelerometer-based indication of activity, and Input #3 may provide an impedance-based indication of respiration, such as minute ventilation. Based on at least one of these and/or other inputs, controller **325** provides an output indication of pacing rate as a control signal delivered to a therapy circuit, such as to ventricular 10 therapy circuit **320**. Ventricular therapy circuit **320** issues pacing pulses based on one or more such control signals received from controller **325**. Control of the pacing rate may be performed by controller **325**, either alone or in combination with peripheral circuits or modules, using software, hardware, firmware, or any combination of the like. The software embodiments provide flexibility in how 15 inputs are processed and may also provide the opportunity to remotely upgrade the device software while still implanted in the patient without having to perform surgery to remove and/or replace the device **105**.

<u>Controller Example 1</u>

Figure **5** is a schematic diagram illustrating generally, by way of example, 20 but not by way of limitation, one conceptualization of portions of controller **325**. At least one signal from ventricular sensing circuit **310** is received by ventricular event module **500**, which recognizes the occurrence of ventricular events included within the signal. Such events are also referred to as "beats," "activations," "depolarizations," "QRS complexes," "R-waves," "contractions." Ventricular event 25 module **500** detects intrinsic events (also referred to as sensed events) from the signal obtained from ventricular sensing circuit **310**. Ventricular event module **500** also detects evoked events (resulting from a pace) either from the signal obtained from ventricular sensing circuit **310**, or preferably from a ventricular pacing control signal obtained from pacing control module **505**, which also triggers the delivery of 30 a pacing stimulus by ventricular therapy circuit **320**. Thus, ventricular events

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include both intrinsic/sensed events and evoked/paced events.

A time interval between successive ventricular events, referred to as a V-V interval, is recorded by a first timer, such as V-V interval timer **510**. A filter **515** computes a "first indicated pacing interval," i.e., one indication of a desired time interval between ventricular events or, stated differently, a desired ventricular heart rate. The first indicated pacing interval is also referred to as a ventricular rate regularization (VRR) indicated pacing interval. In various embodiments, filter **515** includes an averager, a weighted averager, a median filter, an infinite (IIR) filter, a finite impulse response (FIR) filter, or any other analog or digital signal processing circuit providing the desired signal processing described more particularly below.

In one embodiment, filter **515** computes a new value of the first indicated pacing interval based on the duration of the most recent V-V interval recorded by timer **510** and on a previous value of the first indicated pacing interval stored in first indicated pacing interval register **520**. Register **520** is then updated by storing the newly computed first indicated pacing interval in register **520**. Based on the first indicated pacing interval stored in register **520**, pacing control module **505** delivers control signals to ventricular therapy circuit **320** for delivering therapy, such as pacing stimuli, at the VRR-indicated ventricular heart rate corresponding to the inverse of the duration of the first indicated pacing interval.

<center>Filter Example 1</center>

In general terms, for one embodiment, device **105** obtains V-V intervals between successive sensed or evoked ventricular beats. Device **105** computes a new first indicated pacing interval based at least in part on the duration of the most recent V-V interval and a previous value of the first indicated pacing interval. Device **105** provides pacing therapy delivered at a rate corresponding to the inverse of the duration of the first indicated pacing interval.

Figure **6** is a signal flow diagram illustrating generally, by way of example, but not by way of limitation, one embodiment of operating filter **515**. Upon the occurrence of a sensed or evoked ventricular beat, timer **510** provides filter **515** with the duration of the V-V interval concluded by that beat, which is referred to as the

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most recent V-V interval (VV_n). Filter **515** also receives the previous value of the first indicated pacing interval (T_{n-1}) stored in register **520**. The most recent V-V interval VV_n and the previous value of the first indicated pacing interval T_{n-1} are each scaled by respective constants A and B, and then summed to obtain a new value of

5   the first indicated pacing interval (T_n), which is stored in register **520** and provided to pacing control module **505**. In one embodiment, the coefficients A and B are different values, and are either programmable, variable, or constant.

If no ventricular beat is sensed during the new first indicated pacing interval T_n, which is measured as the time from the occurrence of the ventricular beat

10   concluding the most recent V-V interval VV_n, then pacing control module **505** instructs ventricular therapy circuit **320** to deliver a ventricular pacing pulse upon the expiration of the new first indicated pacing interval T_n. In one embodiment, operation of the filter is described by $T_n = A \cdot VV_n + B \cdot T_{n-1}$, where A and B are coefficients (also referred to as "weights"), VV_n is the most recent V-V interval

15   duration, and T_{n-1} is the previous value of the first indicated pacing interval.

Initialization of filter **515** includes seeding the filter by storing, in register **520**, an initial interval value. In one embodiment, register **520** is initialized to an interval value corresponding to a lower rate limit (LRL), i.e., a minimum rate at which pacing pulses are delivered by device **105**. Register **520** could alternatively

20   be initialized with any other suitable value.

<u>Filter Example 2</u>

In one embodiment, operation of filter **515** is based on whether the beat concluding the most recent V-V interval VV_n is a sensed/intrinsic beat or a paced/evoked beat. In this embodiment, the pacing control module **505**, which

25   controls the timing and delivery of pacing pulses, provides an input to filter **515** that indicates whether the most recent V-V interval VV_n was concluded by an evoked beat initiated by a pacing stimulus delivered by device **105**, or was concluded by an intrinsic beat sensed by ventricular sensing circuit **310**.

In general terms, if the most recent V-V interval VV_n is concluded by a

30   sensed/intrinsic beat, then filter **515** provides a new first indicated pacing interval T_n

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that is adjusted from the value of the previous first indicated pacing interval T_{n-1} such as, for example, decreased by an amount that is based at least partially on the duration of the most recent V-V interval VV_n and on the duration of the previous value of the first indicated pacing interval T_{n-1}. If, however, the most recent V-V

5   interval VVn is concluded by a paced/evoked beat, then filter 515 provides a new first indicated pacing interval T_n that is increased from the value of the previous first indicated pacing interval T_{n-1}, such as, for example, by an amount that is based at least partially on the duration of the most recent V-V interval VV_n and on the duration of the previous value of the first indicated pacing interval T_{n-1}. If no

10   ventricular beat is sensed during the new first indicated pacing interval T_n, which is measured as the time from the occurrence of the ventricular beat concluding the most recent V-V interval VV_n, then pacing control module 505 instructs ventricular therapy circuit 320 to deliver a ventricular pacing pulse upon the expiration of the new first indicated pacing interval T_n.

15   Figure 7 is a signal flow diagram, illustrating generally, by way of example, but not by way of limitation, another conceptualization of operating filter 515, with certain differences from Figure 6 more particularly described below. In this embodiment, the pacing control module 505, which controls the timing and delivery of pacing pulses, provides an input to filter 515 that indicates whether the most

20   recent V-V interval VV_n was concluded by an evoked beat initiated by a pacing stimulus delivered by device 105, or was concluded by an intrinsic beat sensed by ventricular sensing circuit 310.

        If the most recent V-V interval VV_n was concluded by an intrinsic beat, then the most recent V-V interval VV_n and the previous value of the first indicated pacing

25   interval T_{n-1} are each scaled by respective constants A and B, and then summed to obtain the new value of the first indicated pacing interval T_n, which is stored in register 520 and provided to pacing control module 505. Alternatively, if the most recent V-V interval VV_n was concluded by a evoked/paced beat, then the most recent V-V interval VV_n and the previous value of the first indicated pacing interval T_{n-1} are

30   each scaled by respective constants C and D, and then summed to obtain the new

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value of the first indicated pacing interval T_n, which is stored in register **520** and provided to pacing control module **505**. In one embodiment, the coefficients C and D are different from each other, and are either programmable, variable, or constant. In a further embodiment, the coefficient C is a different value from the coefficient A, and/or the coefficient D is a different value than the coefficient B, and these coefficients are either programmable, variable, or constant. In another embodiment, the coefficient D is the same value as the coefficient B.

In one embodiment, operation of filter **515** is described by $T_n = A \cdot VV_n + B \cdot T_{n-1}$, if VV_n is concluded by an intrinsic beat, and is described by $T_n = C \cdot VV_n + D \cdot T_{n-1}$, if VV_n is concluded by a paced beat, where A, B, C and D are coefficients (also referred to as "weights"), VV_n is the most recent V-V interval duration, T_n is the new value of the first indicated pacing interval, and T_{n-1} is the previous value of the first indicated pacing interval. If no ventricular beat is sensed during the new first indicated pacing interval T_n, which is measured as the time from the occurrence of the ventricular beat concluding the most recent V-V interval VV_n, then pacing control module **505** instructs ventricular therapy circuit **320** to deliver a ventricular pacing pulse upon the expiration of the new first indicated pacing interval T_n.

<center>Filter Example 3</center>

In another embodiment, these coefficients can be more particularly described using an intrinsic coefficient (a), a paced coefficient (b), and a weighting coefficient (w). In one such embodiment, $A = a \cdot w$, $B = (1-w)$, $C = b \cdot w$, and $D = (1-w)$. In one example, operation of the filter **515** is described by $T_n = a \cdot w \cdot VV_n + (1-w) \cdot T_{n-1}$, if VV_n is concluded by an intrinsic beat, otherwise is described by $T_n = b \cdot w \cdot VV_n + (1-w) \cdot T_{n-1}$, if VV_n is concluded by a paced beat, as illustrated generally, by way of example, but not by way of limitation, in the signal flow graph of Figure **8**. If no ventricular beat is sensed during the new first indicated pacing interval T_n, which is measured as the time from the occurrence of the ventricular beat concluding the most recent V-V interval VV_n, then pacing control module **505** instructs ventricular therapy circuit **320** to deliver a ventricular pacing pulse upon the expiration of the new first indicated pacing interval T_n. In one embodiment, the coefficients a and b are

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different from each other, and are either programmable, variable, or constant.

The above-described parameters (e.g., A, B, C, D, a, b, w) are stated in terms of time intervals (e.g., VV_n, T_n, T_{n-1}). However, an alternate system may produce results in terms of rate, rather than time intervals, without departing from the present

5 method and apparatus. In one embodiment, weighting coefficient w, intrinsic coefficient a, and paced coefficient b, are variables. Different selections of w, a, and b, will result in different operation of the present method and apparatus. For example, as w increases the weighting effect of the most recent V-V interval VV_n increases and the weighting effect of the previous first indicated pacing rate T_{n-1}

10 decreases. In one embodiment, $w = 1/16 = 0.0625$. In another embodiment, $w = 1/32$. Another possible range for w is from $w = \frac{1}{2}$ to $w = 1/1024$. A further possible range for w is from $w \approx 0$ to $w \approx 1$. Other values of w, which need not include division by powers of two, may be substituted without departing from the present method and apparatus.

15 In one embodiment, intrinsic coefficient a, is selected to be greater than 0.5, or to be greater than 1.0. In one example, the intrinsic coefficient a is selected to be lesser in value than the pacing coefficient b. In one example, $a \approx 1.1$ and $b \approx 1.2$. In another embodiment $a = 0.9$ and $b = 1.1$. One possible range for a is from $a = 0.5$ to $a = 2.0$, and for b is from $b = 1.0$ to $b = 3.0$. The coefficients may vary without

20 departing from the present method and apparatus.

In one embodiment, for $b > 1$ and for substantially regular V-V intervals, filter 515 provides a new first indicated pacing interval T_n that is at least slightly longer than the expected intrinsic V-V interval being measured by timer 515. Thus, if the intrinsic V-V interval being timed is consistent with the duration of previously

25 received V-V intervals, then filter 515 avoids triggering a pacing stimulus. In such a case, a pacing pulse is delivered only if the presently timed V-V interval becomes longer than the previous substantially constant V-V intervals. In general terms, filter 515 operates so that pacing pulses are typically inhibited if the ventricular rate is substantially constant. However, if the measured V-V intervals become irregular,

30 then filter 515 operates, over a period of one or several such V-V intervals, to

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shorten the first indicated pacing interval T_n so that pacing stimuli are being delivered.

According to one aspect of the invention, it is believed that if the irregular V-V intervals are caused by a conducted atrial tachyarrhythmia, then pacing the
5   ventricle will regularize the ventricular heart rate by establishing retrograde conduction from the ventricle. This, in turn, blocks forward conduction of atrial signals through the atrioventricular (A-V) node. As a result, irregular atrial signals do not trigger resulting irregular ventricular contractions. According to another aspect of the invention, however, this method and apparatus will not introduce
10   pacing pulses until the heartbeat becomes irregular. Therefore, the heart is assured to pace at its intrinsic rate when regular ventricular contractions are sensed.

Controller Example 2

Figure **9** is a schematic diagram illustrating generally, by way of example, but not by way of limitation, another conceptualization of portions of controller **325**,
15   with certain differences from Figure **5** more particularly described below. In Figure **9**, controller **325** receives from sensor **330** a signal including information from which a physiologically desired heart rate (e.g., based on the patient's activity, respiration, or any other suitable indicator of metabolic need) can be derived. The sensor signal is digitized by an A/D converter **900**. The digitized signal is processed
20   by a sensor rate module **905**, which computes a desired heart rate that is expressed in terms of a second indicated pacing interval stored in register **910**.

Pacing control module **505** delivers a control signal, which directs ventricular therapy circuit **320** to deliver a pacing pulse, based on either (or both) of the first or second indicated pacing intervals, stored in registers **520** and **910**,
25   respectively, or both. In one embodiment, pacing control module **505** includes a selection module **915** that selects between the new first indicated pacing interval T_n and the sensor-based second indicated pacing interval.

In one embodiment, selection module **915** selects the shorter of the first and second indicated pacing intervals as the selected indicated pacing interval S_n. If no
30   ventricular beat is sensed during the selected indicated pacing interval S_n, which is

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measured as the time from the occurrence of the ventricular beat concluding the most recent V-V interval VV_n, then pacing control module **505** instructs ventricular therapy circuit **320** to deliver a ventricular pacing pulse upon the expiration of the selected indicated pacing interval S_n.

5   In general terms, for this embodiment, the ventricle is paced at the higher of the sensor indicated rate and the VRR indicated rate. If, for example, the patient is resting, such that the sensor indicated rate is lower than the patient's intrinsic rate, and the patient's intrinsic rate is substantially constant, then the intrinsic rate is higher than the VRR indicated rate. As a result, pacing pulses generally will not be

10   delivered. But if, for example, the patient is resting, but with an atrial tachyarrhythmia that induces irregular ventricular contractions, then pacing pulses generally will be delivered at the VRR indicated rate. In another example, if the patient is active, such that the sensor indicated rate is higher than the VRR indicated rate, then pacing pulses generally will be delivered at the sensor indicated rate. In

15   an alternative embodiment, the pacing rate is determined by blending the sensor indicated rate and the VRR indicated rate, rather than by selecting the higher of these two indicated rates (i.e., the shorter of the first and second indicated pacing intervals).

In another embodiment, selection module **915** provides a selected indicated

20   pacing interval S_n based on a blending of both the first and second indicated pacing intervals. In one such example, selection module **915** applies predetermined or other weights to the first and second indicated pacing intervals to compute the selected pacing interval S_n.

<u>Controller Example 2</u>

25   Figure **10** is a schematic diagram illustrating generally, by way of example, but not by way of limitation, another conceptualization of portions of controller **325**, with certain differences from Figure **9** more particularly described below. In Figure **10**, controller **325** includes an atrial tachyarrhythmia (AT) detection module **1000** that receives a signal from atrial sensing circuit **305**. The received signal includes

30   information about atrial events, from which AT detection module **1000** determines

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the presence or absence of one or more atrial tachyarrhythmias, such as atrial fibrillation.

In one embodiment, AT detection module **1000** provides a control signal, to pacing control module **505**, that indicates the presence or absence of an atrial

5 tachyarrhythmia, such as atrial fibrillation. In one embodiment, selection module **915** selects between the first and second indicated pacing intervals as illustrated, by way of example, but not by way of limitation, in Table 1.

Table 1. Example Selection Based on AT Detection, 1st Indicated Pacing Interval,

10 and 2nd Indicated Pacing Interval

AT Present?	*1st Indicated Pacing Interval < 2nd Indicated Pacing Interval ?*	*1st Indicated Pacing Interval ≥ 2nd Indicated Pacing Interval ?*
Yes, AT Present	$S_n \leftarrow$ 1st Indicated Pacing Interval (i.e., VRR)	$S_n \leftarrow$ 2nd Indicated Pacing Interval (e.g., Sensor)
No, AT not Present	$S_n \leftarrow$ 2nd Indicated Pacing Interval (e.g., Sensor)	$S_n \leftarrow$ 2nd Indicated Pacing Interval (e.g., Sensor)

15 In this embodiment, if an atrial tachyarrhythmia is present and the first indicated pacing interval is shorter than the second indicated pacing interval, then selection module **915** selects the first indicated pacing interval, which is based on the VRR techniques described above, as the selected indicated pacing interval S_n. Otherwise, selection module **915** selects the second indicated pacing interval, which

20 in one embodiment is based on the sensor indications, as the selected indicated pacing interval S_n. As discussed above, if no ventricular beat is sensed during the selected indicated pacing interval S_n, which is measured as the time from the occurrence of the ventricular beat concluding the most recent V-V interval VV_n, then pacing control module **505** instructs ventricular therapy circuit **320** to deliver a

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ventricular pacing pulse upon the expiration of the selected indicated pacing interval S_n.

Stated differently, for this embodiment, the ventricle is paced at the VRR indicated rate only if an atrial tachyarrhythmia, such as atrial fibrillation, is present

5 and the VRR indicated rate exceeds the sensor indicated rate. Otherwise the ventricle is paced at the sensor indicated rate. If, for example, the patient is resting, such that the sensor indicated rate is lower than the patient's intrinsic rate, and no atrial tachyarrhythmia is present, then the device will sense the intrinsic rate or will deliver ventricular paces at the lower rate limit. But if, for example, the patient is

10 resting, but with an atrial tachyarrhythmia that induces irregular ventricular contractions, then pacing pulses generally will be delivered at the VRR indicated rate. In another example, if the patient is active, such that the sensor indicated rate is higher than the VRR indicated rate, then pacing pulses generally will be delivered at the sensor indicated rate, whether or not atrial tachyarrhythmia is present. As an

15 alternative to the selection described with respect to Table 1, selection module **915** provides a fixed or variable weighting or blending of both the sensor-indicated rate and VRR indicated rate, such that pacing pulses are delivered based on the blended rate.

The second indicated pacing interval need not be based on sensor

20 indications. In one embodiment, for example, the second indicated pacing interval tracks the sensed atrial heart rate when no atrial tachyarrhythmia is present. In this embodiment, selection module **915** performs a mode-switching function in which the first indicated pacing interval is used whenever atrial tachyarrhythmia is present and the second indicated pacing interval (e.g., atrial-tracking) is used when no atrial

25 tachyarrhythmia is present.

In another embodiment, heart rate/interval is used as a trigger turn on/off use of the first indicated pacing interval (e.g., the VRR indicated pacing interval). In one example, pacing therapy is based on the first indicated pacing interval if the first indicated pacing interval is longer than a first predetermined value, and pacing

30 therapy is substantially independent of the first indicated pacing interval if the first

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indicated pacing interval is shorter than the first predetermined value. In this example, the VRR indicated pacing interval is used at low heart rates, but not at fast heart rates.

Filter Rate Behavior Example 1

5   Figure **11** is a graph illustrating generally, by way of example, but not by way of limitation, one embodiment of a VRR indicated rate for successive ventricular heart beats for one mode of operating filter **515**. As discussed above, the VRR indicated rate is simply the frequency, between ventricular heart beats, associated with the first indicated pacing interval. Stated differently, the VRR

10   indicated rate is the inverse of the duration of the first indicated pacing interval. If pacing is based solely on the VRR indicated rate, pacing control module **505** directs ventricular therapy circuit **320** to issue a pacing pulse after the time since the last ventricular beat equals or exceeds the first indicated pacing interval. However, as described above, in certain embodiments, pacing control module **505** directs

15   ventricular therapy circuit **320** to issue a pacing pulse based on factors other than the VRR indicated rate such as for, example, based on the sensor indicated rate.

      In the example illustrated in Figure **11**, a first sensed intrinsic ventricular beat, indicated by an "S" was detected just before expiration of the first indicated pacing interval ("VRR indicated pacing interval") T_0, as computed based on a

20   previous ventricular beat. In one embodiment, the new VRR indicated pacing interval T_1 is computed based on the duration of most recent V-V interval VV_1 and a previous value of the VRR indicated pacing interval T_0, as discussed above. In this example, the new VRR indicated pacing interval T_1 corresponds to a lower rate limit (LRL) time interval. In one embodiment, the allowable range of the VRR indicated

25   pacing interval is limited so that the VRR indicated pacing interval does not exceed the duration of the LRL time interval, and so that the VRR indicated pacing interval is not shorter than the duration of an upper rate limit (URL) time interval.

      The second ventricular beat is also sensed, just before expiration of the VRR indicated pacing interval T_1. In one embodiment, the new VRR indicated pacing

30   interval T_2 is computed based on the duration of most recent V-V interval VV_2 and a

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previous value of the VRR indicated pacing interval, T_1, as discussed above. The first and second ventricular beats represent a stable intrinsic rhythm, for which no pacing is delivered because the VRR indicated pacing interval is at a lower rate than the sensed intrinsic ventricular beats.

5   The third, fourth, and fifth ventricular beats represent the onset of atrial fibrillation, resulting in erratic ventricular rates. The third ventricular beat is sensed well before expiration of the VRR indicated pacing interval T_2, such that no pacing pulse is issued. For the sensed third ventricular beat, filter **515** computes the new VRR indicated pacing interval T_3 as being shorter in duration relative to the previous

10   VRR indicated pacing interval T_2.

The fourth ventricular beat is similarly sensed well before expiration of the VRR indicated pacing interval T_3, such that no pacing pulse is issued. For the sensed fourth ventricular beat, filter **515** computes the new VRR indicated pacing interval T_4 as being shorter in duration relative to the previous VRR indicated pacing

15   interval T_3.

The fifth ventricular beat is sensed before expiration of the VRR indicated pacing interval T_4, such that no pacing pulse is issued. For the sensed fifth ventricular beat, filter **515** computes the new VRR indicated pacing interval T_5 as being shorter in duration relative to the previous VRR indicated pacing interval T_4.

20   The sixth, seventh, and eighth ventricular beats indicate regularization of the ventricular rate using the pacing techniques described above. No ventricular beat is sensed during the VRR indicated pacing interval T_5, so a pacing pulse is issued to evoke the sixth ventricular beat. A new VRR indicated pacing interval T_6 is computed as being increased in duration relative to the previous VRR indicated

25   pacing interval T_5, lowering the VRR indicated rate. Similarly, no ventricular beat is sensed during the VRR indicated pacing interval.

The ninth ventricular beat represents another erratic ventricular beat resulting from the atrial fibrillation episode. The ninth ventricular beat is sensed before expiration of the VRR indicated pacing interval T_8. As a result, a shorter new VRR

30   indicated pacing interval T_9 is computed.

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The tenth and eleventh ventricular beats illustrate further regularization of the ventricular rate using the pacing techniques described above. No ventricular beat is sensed during the VRR indicated pacing interval T_9, so a pacing pulse is issued to evoke the tenth ventricular beat. A new VRR indicated pacing interval T_{10}

5   is computed as being increased in duration relative to the previous VRR indicated pacing interval T_9, lowering the VRR indicated rate. Similarly, no ventricular beat is sensed during the VRR indicated pacing interval T_{10}, so a pacing pulse is issued to evoke the tenth ventricular beat. A new VRR indicated pacing interval T_{11} is compute as being increased in duration relative to the previous VRR indicated

10   pacing interval T_{10}, lowering the VRR indicated rate.

The twelfth, thirteenth, fourteenth, and fifteenth ventricular beats illustrate resumption of a stable intrinsic rhythm after termination of the atrial fibrillation episode. For such a stable rate, the VRR indicated rate proceeds asymptotically toward a "floor value" that tracks, but remains below, the intrinsic rate. This allows

15   the intrinsic heart signals to control heart rate when such intrinsic heart signals provide a stable rhythm. As a result, when the patient's intrinsic rate is constant, paces will be withheld, allowing the patient's intrinsic heart rhythm to continue. If the patient's heart rate includes some variability, and the VRR indicated floor value is close to the mean intrinsic heart rate, then occasional paced beats will occur.

20   Such pace beats will gradually lengthen the VRR indicated pacing interval, thereby allowing subsequent intrinsic behavior when the patient's heart rate becomes substantially constant.

The intrinsic coefficient a of filter **515** controls the "attack slope" of the VRR indicated heart rate as the VRR indicated heart rate increases because of

25   sensed intrinsic beats. The paced coefficient b of filter **515** controls the "decay slope" of the VRR indicated heart rate as the VRR indicated heart rate decreases during periods of paced beats. In one embodiment, in which $a > 1.0$ and $b > 1.0$, decreasing the value of a toward 1.0 increases the attack slope such that the VRR indicated rate increases faster in response to sensed intrinsic beats, while decreasing

30   the value of b toward 1.0 decreases the decay slope such that the VRR indicated rate

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decreases more slowly during periods of paced beats. Conversely, for $a > 1.0$ and $b > 1.0$, increasing the value of a from 1.0 decreases the attack slope such that the VRR indicated rate increases more slowly in response to sensed intrinsic beats, while increasing the value of b from 1.0 increases the decay slope such that the

5 VRR-indicated rate decreases more quickly during periods of paced beats.

In one embodiment, for $a > 1.0$ and $b > 1.0$, decreasing both a and b toward 1.0 increases VRR indicated rate during periods of sensed intrinsic activity so that the VRR indicated rate is closer to the mean intrinsic rate. Because the VRR indicated rate is closer to the mean intrinsic rate, variability in the intrinsic heart rate

10 is more likely to trigger paces at the VRR indicated rate. On the other hand, for $a > 1.0$ and $b > 1.0$, increasing both a and b from 1.0 decreases the VRR indicated rate during periods of sensed intrinsic activity so that the VRR indicated rate is farther beneath the mean intrinsic rate. Because the VRR indicated rate is farther beneath the mean intrinsic rate, the same variability in the intrinsic heart rate becomes less

15 likely to trigger paces at the VRR indicated rate.

In one embodiment, these coefficients are programmable by the user, such as by using remote programmer **125**. In another embodiment, the user selects a desired performance parameter (e.g., desired degree of rate regularization, desired attack slope, desired decay slope, etc.) from a corresponding range of possible values, and

20 device **105** automatically selects the appropriate combination of coefficients of filter **515** to provide a filter setting that corresponds to the selected user-programmed performance parameter, as illustrated generally by Table **2**. Other levels of programmability or different combinations of coefficients may also be used.

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Table **2**. *Example of Automatic Selection of Aspects of Filter Setting Based on a User-Programmable Performance Parameter.*

User-Programmable Performance Parameter	Intrinsic Coefficient *a*	Paced Coefficient *b*
1 (Less Rate Regularization)	2.0	3.0
2	1.8	2.6
3	1.6	2.2
4	1.4	1.8
5	1.2	1.4
6 (More Rate Regularization)	1.0	1.0

Filter Rate Behavior Example 2

Figure **12** is a graph illustrating generally, by way of example, but not by way of limitation, one embodiment of selecting between more than one indicated pacing interval. Figure **12** is similar to Figure **11** in some respects, but Figure **12** includes a second indicated pacing interval. In one embodiment, the first indicated pacing interval is the VRR indicated pacing interval, described above, and the second indicated pacing interval is a sensor indicated pacing interval, from an accelerometer, minute ventilation, or other indication of the patient's physiological need for increased cardiac output.

In one embodiment, a selected indicated pacing interval is based on the shorter of the first and second indicated pacing intervals. Stated differently, device **105** provides pacing pulses at the higher indicated pacing rate. In the example illustrated in Figure **12**, first and second beats and the twelfth through fifteenth beats are paced at the sensor indicated rate, because it is higher than the VRR indicated rate and the intrinsic rate. The third, fourth, fifth, and ninth beats are sensed intrinsic beats that are sensed during the shorter of either of the VRR and sensor

indicated pacing intervals. The sixth through eighth beats and tenth and eleventh beats are paced at the VRR indicated rate, because it is higher than the sensor indicated rate. Also, for these beats, no intrinsic beats are sensed during the VRR indicated intervals. In one embodiment, the above-described equations for filter **515**

5 operate to increase the VRR indicated rate toward the sensor-indicated rate when the sensor indicated rate is greater than the VRR indicated rate, as illustrated by first through third and twelfth through fifteenth beats in Figure **12**. In an alternate embodiment, however, $T_n = b \cdot w \cdot VV_n + (1-w) \cdot T_{n-1}$, if VV_n is concluded by a VRR indicated paced beat, and $T_n = T_{n-1}$ if VV_n is concluded by a sensor indicated paced

10 beat, thereby leaving the VRR indicated rate unchanged for sensor indicated paced beats.

In this embodiment, the ranges of both the sensor indicated rate and the VRR indicated rate are limited so that they do not extend to rates higher than the URL or to rates lower than the LRL. In one embodiment, the LRL and the URL are

15 programmable by the user, such as by using remote programmer **125**.

In a further embodiment, the selected indicated pacing interval is based on the shorter of the first and second indicated pacing intervals only if an atrial tachyarrhythmia, such as atrial fibrillation, is present. Otherwise, the second indicated pacing interval is used, as described above.

20   Filter Rate Behavior Example 3

Figure **13** is a graph illustrating generally, by way of example, but not by way of limitation, another illustrative example of heart rate vs. time according to a spreadsheet simulation of the behavior of the above-described VRR algorithm. In Figure **13**, the VRR algorithm is turned off until time 130. Stable intrinsic lower

25 rate behavior is modeled for times between 0 and 10 seconds. Erratic intrinsic ventricular rates, such as would result from atrial tachyarrhythmias including atrial fibrillation, are modeled during times between 10 seconds and 130 seconds. At time 130 seconds, the VRR algorithm is turned on. While some erratic intrinsic beats are subsequently observed, the VRR algorithm provides pacing that is expected to

30 substantially stabilize the heart rate, as illustrated in Figure **13**. The VRR indicated

pacing rate gradually decreases until intrinsic beats are sensed, which results in a slight increase in the VRR indicated pacing rate. Thus, the VRR algorithm favors the patient's intrinsic heart rate when it is stable, and paces at the VRR indicated heart rate when the patient's intrinsic heart rate is unstable. It is noted that Figure

5   13 does not represent clinical data, but rather provides a simulation model that illustrates one example of how the VRR algorithm is expected to operate.

<div align="center">Filter Example 4</div>

In one embodiment, filter **515** includes variable coefficients such as, for example, coefficients that are a function of heart rate (or its corresponding time

10   interval). In one example, operation of the filter **515** is described by $T_n = a \cdot w \cdot VV_n + (1-w) \cdot T_{n-1}$, if VV_n is concluded by an intrinsic beat, otherwise is described by $T_n = b \cdot w \cdot VV_n + (1-w) \cdot T_{n-1}$, if VV_n is concluded by a paced beat, where at least one of a and b are linear, piecewise linear, or nonlinear functions of one or more previous V-V intervals such as, for example, the most recent V-V interval, VV_n.

15   Figure **14** is a graph illustrating generally, by way of example, but not by way of limitation, one embodiment of using at least one of coefficients a and b as a function of one or more previous V-V intervals such as, for example, the most recent V-V interval VV_n. In one such example, a is less than 1.0 when VV_n is at or near the lower rate limit (e.g., 1000 millisecond interval or 60 beats/minute), and a

20   is greater than 1.0 when VV_n is at or near the upper rate limit (e.g., 500 millisecond interval or 120 beats/minute). For a constant b, using a smaller value of a at lower rates will increase the pacing rate more quickly for sensed events; using a larger value of a at higher rates increases the pacing rate more slowly for sensed events. In another example, b is close to 1.0 when VV_n is at or near the lower rate limit, and b

25   is greater than 1.0 when VV_n is at or near the upper rate limit. For a constant a, using a smaller value of b at lower rates will decrease the pacing rate more slowly for paced events; using a larger value of b at higher rates decreases the pacing rate more quickly for paced events.

<div align="center">Conclusion</div>

30   It is to be understood that the above description is intended to be illustrative,

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and not restrictive. Many other embodiments will be apparent to those of skill in the art upon reviewing the above description. The scope of the invention should, therefore, be determined with reference to the appended claims, along with the full scope of equivalents to which such claims are entitled.

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